

Behavior-Based Control Systems for Planetary Autonomous Robot Outposts

Terry Huntsberger, Hrand Aghazarian, Eric Baumgartner, Paul S. Schenker
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109
(818)354-5794, (818)354-1429, (818)354-3841, (818)354-2681
terry.huntsberger,hrand.aghazarian,eric.baumgartner,paul.s.schenker@jpl.nasa.gov

Abstract— Current NASA studies are examining opportunities for the deployment of robot colonies or outposts on planetary surfaces within the solar system in the first few decades of the 21st century. This paper presents the results of some ongoing work in the Planetary Robotics Laboratory at JPL in the area of behavior-based control for cooperative multi-robot systems for a planetary robot outpost. We have recently developed a behavior-based system called BISMARC (Biologically Inspired System for Map-based Autonomous Rover Control) that uses a free flow hierarchy for its action selection mechanism. We report the results of numerous simulation studies of complicated multiple rover missions.

Key words: robot outpost, behavior-based control, multi-robot systems

TABLE OF CONTENTS

1. INTRODUCTION
2. BISMARC OVERVIEW
3. EXPERIMENTAL STUDIES
4. CONCLUSIONS
5. ACKNOWLEDGMENTS
6. REFERENCES

1. INTRODUCTION

Robot outposts represent the next stage of exploration for NASA planetary surface studies beyond the Mars Sample Return missions of 2003/2005. Outpost operations include such tasks as the deployment and servicing of power systems and in-situ resource utilization (ISRU) generators, establishing long-life robotic science stations for measurement and communications, construction of beacons, roadways, and the site preparation and deployment of human

habitat modules. These outposts must be more or less self-sustaining due to the high cost of resupply. Robot autonomy within the context of a remote outpost will be constrained by mission mass restrictions, and the harsh nature of planetary surfaces. Among these constraints are relatively low computing capabilities and onboard memory due to power constraints, operation within wide temperature extremes, and navigation over multiple terrain types from featureless flat plains to sheer cliffs. In addition, the complexity of the tasks undertaken by robots making up an outpost push the limits of current control capabilities. A discussion of the needed capabilities for robotic systems for outposts can be found in the study done by Huntsberger, Rodriguez and Schenker [13].

Control architectures for robotic systems can be broadly characterized as planning or deliberative, behavior-based or reactive, and hybrid blends of the methods [19]. The planning systems usually have a high computational overhead and require an environment that is relatively static. A representative system is that of Kosaka and Kak [14]. Reactive control systems, on the other hand, are based on a mapping between sensor inputs and actuators, and as such, tend to sacrifice optimality and goal convergence guarantees for more or less real-time response. Such systems were introduced by Brooks [4] and further extended by Arkin [1], Parker [18], and Mataric [17] among others. The Autonomous Robot Architecture (AuRA) [1], Atlantis [5], and the Planner-Reactor Architecture [16] are some examples of hybrid control systems.

Recently, reactive control systems have gained popularity for controlling mobile robotic platforms on planetary surfaces. This was demonstrated to some extent by the Mars Sojourner mission in the summer of 1997. Two laboratory prototype rover systems for planetary surface missions include the Sample Return Rover (SRR) and the Field Integrated Design and Operations (FIDO) rover, both shown in Figure 1, which are currently being field tested at the Jet Propulsion Laboratory in Pasadena, CA, USA. These rovers are among a wide class of planetary surface rovers developed at JPL which include the Long Range Science Rover Rocky 7. SRR is built for low mass, high speed and

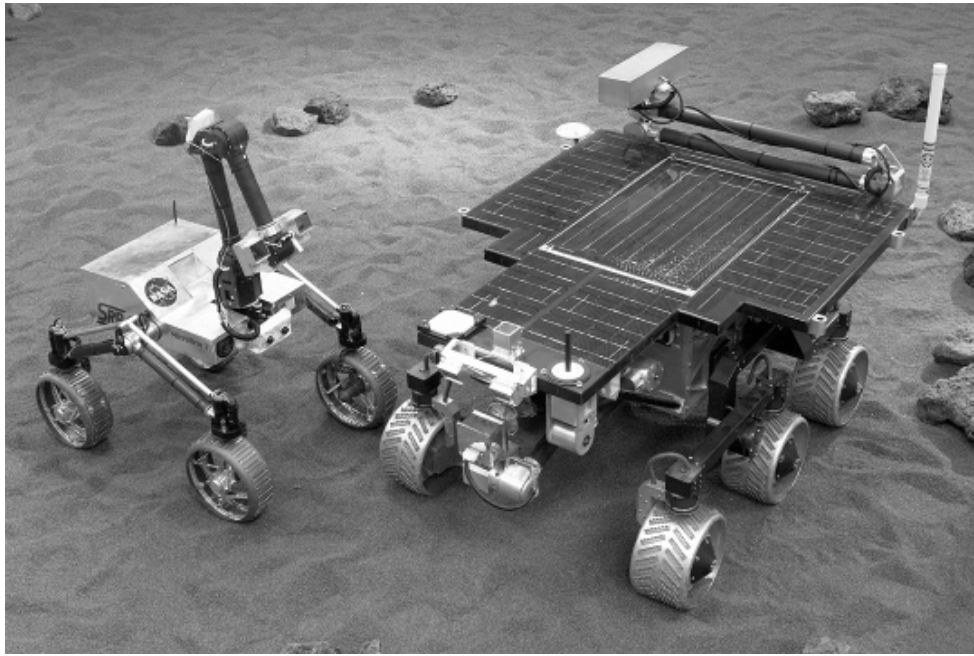


Figure 1 SRR and FIDO rover prototypes in the Planetary Robotics Lab at the Jet Propulsion Laboratory in Pasadena, CA, USA.

mobility, while FIDO includes a full science suite equivalent to the 2003 Athena system. These rovers use a traditional finite state control system for navigation and goal achievement. Such a reactive approach doesn't scale well when multiple rovers are cooperating on a task, due to the large number of potential states that can occur.

Behavior-based systems approach autonomy from the standpoint of collections of behaviors. These run the gamut from the purely subsumptive, reactive single robots detailed by Brooks [4] to cooperative multiple robot systems [2, 3]. The wide range of possible behaviors that are needed for a planetary rover obviates the need for an action selection mechanism (ASM) to provide the correct behavior for any given situation. Comprehensive reviews of behavior coordination (or action selection) mechanisms can be found in Arkin [3] and Pirjanian [19]. Recent work of Pirjanian and Mataric [19, 20, 21] using Multiple Objective Decision Making (MODM) provides formal tools for generating strategies that can guarantee an appropriate trade-off between the optimal solutions, which are possibly not reachable in a planetary surface environment, and *Pareto-optimal* or *Satisficing* solutions.

BISMARC (**B**Biologically **I**nspired **S**ystem for **M**ap-based **A**utonomous **R**over **C**ontrol) is a hybrid wavelet/neural network based system under development at JPL [12]. The BISMARC architecture is shown in Figure 2. Previous simulations demonstrated that the system is capable of control for multiple rovers for multiple cache recovery [6] or manned habitat site preparation [11]. Another study

extended BISMARC to include fault tolerance in the sensing and mechanical rover subsystems [7]. The vision subsystem in the original BISMARC implementation relied on the generalization capabilities of a fuzzy self-organizing feature map (FSOFM) neural network [8]. A better vision subsystem based on camera models combined with tilt sensors that is fully integrated into the BISMARC framework was recently developed [9]. A comprehensive review of neural network systems for rover navigation and control can be found in Huntsberger and Rose [12]. The next section gives a general overview of BISMARC, followed by some experimental studies and a concluding section.

2. BISMARC OVERVIEW

The original BISMARC system had three levels and used a hybrid mix of neural networks and behavior-based approaches [12]. The first level performed a wavelet transform on the rover's stereo image pair, the second level input these processed images into an action generation navigation network, which fed into a third level action selection mechanism (ASM) network modeled after the DAMN architecture of Rosenblatt and Payton [22]. The first and second levels of BISMARC have been replaced with the DriveMaps path selection system currently used on SRR and FIDO at JPL [10]. DriveMaps determines clear paths and obstacles (subsequently used as landmarks) from the stereo

pairs of wide field-of-view hazard cameras on the front and back of the rovers. When coupled with onboard rover components such as accelerometers and wheel encoder inputs, an egocentric map of the environment is built using the DriveMaps response as an index.

The BISMARC ASM for a cache recovery task is shown in Figure 3. The collection of behaviors used by BISMARC can be broadly broken into two categories: survival (i.e. Avoid Dangerous Places), and task specific (i.e. Scan for Cache). Most tasks will share the same survival behaviors, which allows the rover to carry a set of task behaviors and

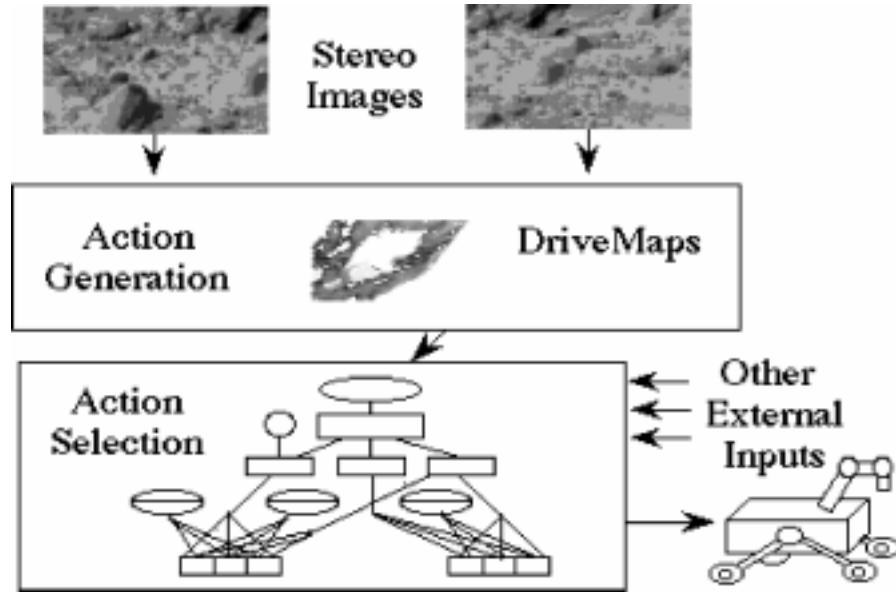


Figure 3 Two level BISMARC architecture with stereo processing, action generation, and action selection subsystems.

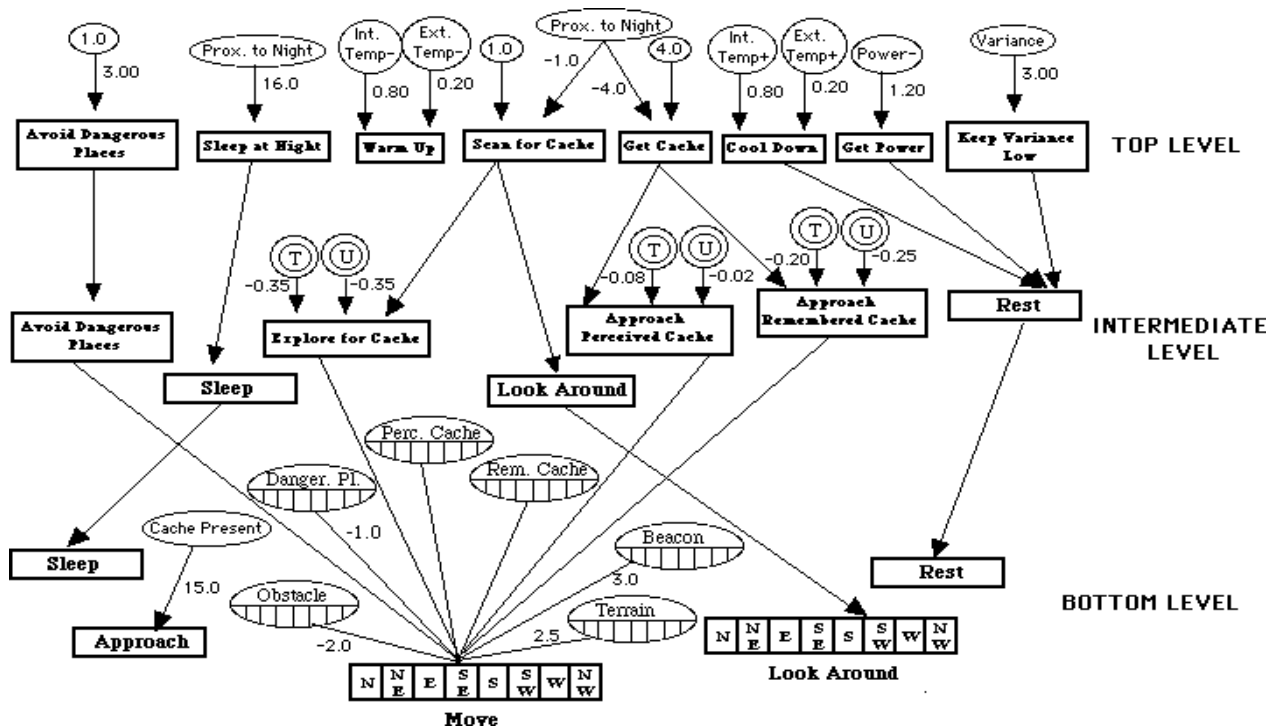


Figure 2 BISMARC ASM for the cache recovery task. The numbers on the links are the weights for the input feed.

switch between them if necessary. The survival behaviors include mobility as well as temperature and battery level preservation measures. Sensor feeds are only done at the appropriate level where needed, which eliminates the potential bottlenecks seen in traditional hierarchical ASMs.

Weights on the links between behaviors perform a type of priority weighting, which will ultimately favor selection of the heaviest weighted action at the bottom level of the hierarchy. For example, the Sleep at Night behavior is the most heavily weighted since absolutely no motion is allowed at night due to the lack of night vision. In the event that sensors such as LIDAR are available, this weighting can be relaxed to allow movement at night. Determination of the optimal set of weights for completion of any task is not mathematically well defined, although recent studies by Pirjanian [19], Yen and Pfluger [25], and Steinhage and Schöner [23] have defined functional definitions of the system dynamics to address this point.

Combination of the weighted links is done in three ways: additive, multiplicative, or through a weighted summation process suggested by Tyrrell [24]. At the bottom level of the ASM hierarchy are the actions that are available to the rover. These include movement, surveillance, survival, and task specific actions. The movement and surveillance actions are direction specific, while the survival ones tend not to be so. Once again, as was the case with the high level behaviors, the rover can carry a set of task specific actions, and select the appropriate set when needed.

Tyrrell introduced the temporal penalty (T-circle in Figure 3) to control action that will take an inordinate amount of time to complete [24]. The temporal penalty is derived using the assigned value raised to the power of the elapsed time during the current action. Temporal penalty nodes increase the likelihood of satisfying the overall mission goal in this example of totally clearing a designated area. In addition, the uncertainty penalty (U-circle in Figure 3) is used to control actions that are heavily dependent on external sensor inputs, which are usually noisy and imprecise.

Mapping of a site is based on the use of information taken at multiple levels of detail. This includes descent imagery, remotely sensed imagery such as that returned by the Mars Global Surveyor, range maps from the onboard sensing suites, wheel odometry, and gyro/accelerometer inputs. The descent and remotely sensed imagery is used to build a coarse level map with a 1 meter grid spacing. This is supplemented by a local map with a 5 cm grid spacing provided by the onboard sensing (stereo cameras) at the "landmarks" such as obstacles, cliffs, habitat modules. These areas are mapped extensively and are used for the sharing of navigational information between robots. The map between these features only includes odometry and directional vector information. This method gives a detailed view of the

environment where it is needed, without the storage overhead that would be associated with fine grid coverage of multi-kilometer sized areas such as those found in an outpost.

Since the environment may change due to climatic occurrences such as dust storms, and the actions of other rovers or manned interaction, BISMARC uses a two-level memory system based on perceived short term memory (STM) inputs and remembered long term memory (LTM) storage. Perceptions are compared to the LTM contents using, at best, uncertain rover localization information. Positional variance is used to weight the match to LTM, with a stronger chance of match in areas of low variance. Variance is kept under control using established landmarks such as a lander or habitat module.

Fault detection is built into the ASM using the following form of sensor activation function:

$$A_s = P_d * (1.0 - \text{dist}) * (1.0 - P_u), \quad (1)$$

where A_s is the activation level for sensor S , P_d is the normalized sensor input, dist is the normalized distance to the perceived objects, and P_u is the perception uncertainty. The perception uncertainty is given by:

$$P_u = \text{ABS} [P_d(t+1) - P_d(t)], \quad (2)$$

where $P_d(t)$ refers to the time separated normalized sensor samples. This expression for P_u experiences a maximum when the sensor input undergoes a full range swing. The perception uncertainty is used for fault detection (high values indicate a possible fault). Sensors with a high uncertainty will have little effect on subsequent nodes. These sensors are flagged, and are allowed to come back on-line if and when the uncertainty stabilizes.

3. EXPERIMENTAL STUDIES

We ran 1000 trials using a random heightfield based on statistical information returned from the Mars Pathfinder mission. The area encompassed about 1 km by 1 km with a grid decomposition resolution of 5 cm at the detailed map level. Each trial had different starting positions and the placement of 4 cache containers was randomized within the area. Three rovers were deployed for each simulated mission: a scout and two retrieval rovers. These rovers had the capabilities of SRR and FIDO respectively. The bandwidth of the communication channel between the rovers is one Megabit/second, which is the same as the modem installed in the current SRR prototype at the Jet Propulsion Laboratory. The top speed on the rovers was set at 25 cm/sec for the scout and 6 cm/sec for the retrieval rovers,

which is consistent with the JPL prototypes. In order to simulate wheel slippage, we set a 15% loss of traction when climbing over a rock or traversing rocky terrain. The battery lifetime was set at one week on all of the rovers and the timestep size for the simulations was fixed at 0.2 sec. All of the rovers were forced to sleep during the night hours of the simulations, since there were no infrared sensors on any of the rovers.

We included a set of possible faults based on a statistical analysis of 200 simulation runs [7]. These faults included loss of one or both stereo cameras in front and back, loss of mobility in one or more wheel sub-assemblies, loss of power regeneration capabilities, loss of one or more wheel encoders, loss of one or more degrees of tilt sensing, and loss of internal temperature sensing capabilities. In the absence of faults the success rate for the cache retrieval task was 98.9%. Faults caused this rate to drop to 16% without fault tolerance, with an increase to 46% with the fault tolerant weight adjustment discussed above.

In another simulation study, we analyzed the site clearing capabilities of a team of six rovers (dozers) that had been modified with a bulldozer-like blade for pushing rocks. A solitary robot can accomplish site clearing if all of the significant rocks are within the size and mass constraints that the robot is able to handle. Rocks that are outside these limits will need to be cleared using a cooperative multiple robot strategy. This strategy is based on an ant food transport study done by Kube and Bonabeau [15], that includes a recruitment behavior for the case when a single robot cannot move a rock. Call for Help, Broadcast, and Respond to Call behaviors are used to implement the strategy.

We ran 100 trials each with colonies of from two to six dozers using a randomly generated height field. The area encompassed a 50x100 meter rectangle with a grid resolution of 5 cm. Each trial had different placement positions for the rocks, with a statistical profile of the Mars Pathfinder mission site used for mass and number of rocks. None of the rocks were allowed to mass over 175 kilograms. It was assumed that the clearing, staging, and rock pile areas were previously delimited by beacons. In addition all of the rocks in the clearance site are assumed to be clearable (no iceberg effect). Top speed on the dozers was set to 30 cm/sec, with a mass of 100 kilograms, and a size of 2x2x1 meter (length, width, height). Power use on the dozers varied continuously from 30 watts when idle, 60 watts when traveling over open terrain, to 110 watts when involved in pushing the heaviest rock within the dozer's capability when alone. This capability was set to a maximum of 75 kilograms. In order to simulate wheel slippage, we set a 20% loss of traction when pushing a rock. A collision between two dozers was considered as totally disabling to both, and a dozer that was hit by a rock being pushed by another dozer was also considered totally disabled. Each

dozer had a forward-facing set of stereo cameras with a baseline of 25 cm, a spatial resolution of 486x512 pixels, and a 100 degree FOV, a transceiver with a bandwidth of 56 kbaud, and an 8 channel receiver for beacon monitoring.

Success in the simulation studies was measured in terms of total time for the task, and the number of dozers that were healthy at the end of the run. Figure 4 plots the total average time taken for the task versus the number of dozers that were allowed to participate up to a maximum of six. The graph starts at two dozers, since there was always at least one rock within the clearing area that was larger than a solitary dozer could move. The performance was not linear, indicating that there is significant interference between the dozers as the total number increases. This behavior manifested itself through more collisions with rocks being pushed by another dozer, more complicated repositioning operations due to the "avoid other robots" behavior, and travel time delays due to the need to maintain a safe distance during the recruitment phase. The rock-dozer collisions were caused by rocks dynamically approaching the about-to-be damaged dozer from an angle outside the range of the forward-facing stereo hazard avoidance cameras.

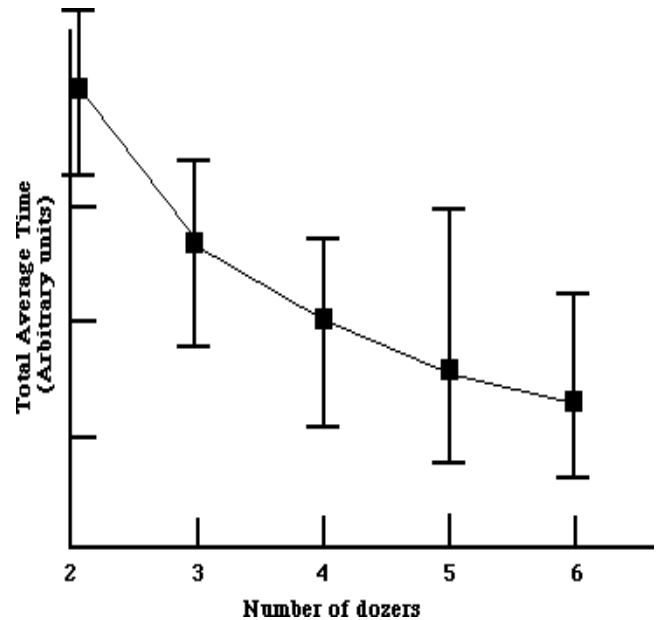


Figure 4 Average total mission times for 500 simulation trials versus the number of dozers in each trial. Time is in arbitrary simulation units with an average time of 3 weeks, 4 days for two dozers. Standard deviations are shown as error bars

4. CONCLUSIONS

This paper has presented a behavior-based system called BISMARC, which is being evaluated for autonomous control of mobile robots in planetary surface outposts. The

system has shown itself in 1500 simulation runs to be capable of successfully completing complicated multirover missions. Although optimality can not be guaranteed using only a behavior-based control system, planning behaviors can also be included in the ASM hierarchy. Fault tolerant adaptation of the weights in between the behaviors has extended the system for long duration capabilities such as the 4 year Mars outpost mission being considered for a launch in 2007. We are currently porting the algorithm to SRR at JPL, and will begin studies within the next few months into cooperative control of two rovers for transporting a solar tent array container to a site prior to deployment. Our earlier study has identified an electrical power system as one of the most important components for early deployment for outpost operations [13].

5. ACKNOWLEDGMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

6. REFERENCES

- [1] R. C. Arkin, "Motor schema based navigation for a mobile robot: An approach to programming by behavior", *Proc. IEEE International Conference on Robotics and Automation (ICRA '87)*, Raleigh, NC, 264-271.
- [2] R. C. Arkin & G. A. Bekey, *Robot Colonies*, Norwell, MA: Kluwer Academic Publishers, 1997.
- [3] R. C. Arkin, *Behavior-Based Robotics*, Cambridge, MA: MIT Press, 1998.
- [4] R. Brooks, "A robust layered control system for a mobile robot", *IEEE Journal of Robotics and Automation*, **2**(1), 14-23, 1986.
- [5] E. Gat, Reliable Goal-Directed Reactive Control of Autonomous Mobile Robots, Ph.D. Dissertation, Virginia Polytechnic Institute, Blacksburg, VA, 1991.
- [6] T. L. Huntsberger, "Autonomous multi-rover system for complex planetary surface retrieval operations", *Proc. Sensor Fusion and Decentralized Control in Autonomous Robotic Systems*, SPIE Vol. 3209, Boston, MA, 220-229, 1997.
- [7] T. L. Huntsberger, "Fault-tolerant action selection for planetary rover control", *Proc. Sensor Fusion and Decentralized Control in Robotic Systems*, SPIE Vol. 3523, Boston, MA, 150-156, 1998.
- [8] T. L. Huntsberger & P. Ajjimarangsee, "Parallel self-organizing feature maps for unsupervised pattern recognition", *International Journal of General Systems*, **16**, 357-372, 1990.
- Also reprinted in *Fuzzy Models for Pattern Recognition*, (Eds. J. C. Bezdek, S. K. Pal), IEEE Press, Piscataway, NJ, 483-495, 1992.
- [9] T. L. Huntsberger, T. Kubota & J. Rose, "Integrated vision/control system for autonomous planetary rovers", *Proc. IAPR Workshop on Machine Vision in Applications*, Chiba, Japan, Nov 1998.
- [10] T. L. Huntsberger, E. T. Baumgartner, H. Aghazarian, Y. Cheng, P. S. Schenker, C. Leger, K. Iagnemma & S. Dubowsky, "Sensor-fused autonomous guidance of a mobile robot and applications to Mars sample return operations", *Proc. Sensor Fusion and Decentralized Control in Robotic Systems II*, SPIE Vol. 3839, Boston, MA, 2-8, 1999.
- [11] T. L. Huntsberger, M. Mataric & P. Pirjanian, "Action selection within the context of a robotic colony", *Proc. Sensor Fusion and Decentralized Control in Robotic Systems II*, SPIE Vol. 3839, Boston, MA, 84-90, 1999.
- [12] T. L. Huntsberger & J. Rose, "BISMARC", *Neural Networks*, **11**(7/8): 1497-1510, 1998.
- [13] T. L. Huntsberger, G. Rodriguez & P. S. Schenker, "Robotics Challenges for Robotic and Human Mars Exploration", to appear in *Proc. Space 2000*, Albuquerque, NM, Mar, 2000.
- [14] A. Kosaka & A. C. Kak, "Fast vision-guided mobile robot navigation using model-based reasoning and prediction of uncertainties", *CVGIP: Image Understanding*, **56**(3), 271-329, 1992.
- [15] C. R. Kube & E. Bonabeau, "Cooperative transport by ants and robots", TR 99--01-008, Santa Fe Institute, Santa Fe, NM, 1999.
- [16] D. Lyons & A. Hendriks, "Planning as incremental adaptation of a reactive system", *Robotics and Autonomous Systems*, **14**(4), 255-288, 1995.
- [17] M. Mataric, Interaction and Intelligent Behavior, Ph.D. Dissertation, Department of EECS, MIT, Cambridge, MA, 1994.
- [18] L. E. Parker, Heterogeneous Multi-Robot Cooperation, Ph.D. Dissertation, Department of EECS, MIT, Cambridge, MA, 1994.
- [19] P. Pirjanian, Multiple Objective Action Selection & Behavior Fusion Using Voting, Ph.D. Dissertation, Department of Medical Informatics and Image Analysis, Aalborg Univ., Denmark, 1998.
- [20] P. Pirjanian, "Multiple Objective Behavior Coordination", to appear in *Journal of Robotics and Autonomous Systems*, 1999.
- [21] P. Pirjanian & M. Mataric, "Multiple Objective vs. Fuzzy Behavior Coordination", to appear in *Lecture Notes in Computer Science, Fuzzy Logic in Mobile Robot Navigation*, 1999.
- [22] J. Rosenblatt & D. Payton, "A fine-grained alternative to the subsumption robot control", *Proc. IEEE/INNS Joint Conf. on Neural Networks*, Washington, DC, 317-324, 1989.
- [23] A. Steinhage & G. Schöner, "Dynamical systems for the behavioral organization of autonomous robot navigation", *Proc. Sensor Fusion and Decentralized Control*

in *Robotic Systems*, SPIE Vol. 3523, Boston, MA, 160-180, 1998.

[24] T. Tyrrell, "The use of hierarchies for action selection", *Journal of Adaptive Behavior*, 1(4), 1993.

[25] J. Yen & N. Pfluger, "A fuzzy logic based extension to Payton and Rosenblatt's command fusion method for mobile robot navigation", *IEEE Transactions on Systems, Man, and Cybernetics*, 25(6), 971-978, 1995.



Terry Huntsberger is a Senior Engineering Scientist with the Engineering Staff in the Mechanical & Robotics Technologies Group at the Jet Propulsion Laboratory in Pasadena, CA. He is an Adjunct Professor and former Director of the Intelligent Systems Laboratory in the Department of Computer Science at

the University of South Carolina. His research interests include behavior-based control, computer vision, neural networks, wavelets, and computer graphics. He has published over 90 technical articles in these and associated areas. He received his B.A. and M.A. degrees in Physics/Math from Hofstra University, and a PhD in Physics from the University of South Carolina. He is a member of SPIE, ACM, IEEE Computer Society, and INNS.



Hrand Aghazarian is a Member of Technical Staff in Telerobotics Research & Applications Group in JPL. He has extensive work experience in the design and development of real-time embedded software for a variety of avionics systems. Currently he is involved in providing software solutions in the

area of software architecture, low-level drivers, motor control, user interfaces for commanding planetary rovers, and navigation algorithm for SRR and FIDO rovers. His research interests are Rover Navigation/Control and Real-Time Embedded software Design and Development. He received a dual B.S. degree in Applied Math and Computer Science and a M.S. degree in Computer Science from California State University in Northridge. He is a member of ACM and INNS societies.



Eric T. Baumgartner is a group leader in the Mechanical and Robotics Technologies Group and a senior member of engineering staff in the Science and Technology Development Section at NASA's Jet Propulsion Laboratory in Pasadena, CA. At JPL, he serves in a systems engineering capacity for the

development of advanced planetary rovers and also contributes to technology developments in the areas of robotic sensing and control. Prior to his tenure at JPL, he was an Assistant Professor in the Mechanical Engineering-Engineering Mechanics Department at Michigan Technological University in Houghton, MI. He has published over 30 articles in the area of robotic controls, and state estimation and is active in the SPIE and ASME. He received his B.S. degree in Aerospace Engineering from the University of Notre Dame, the M.S. degree in Aerospace Engineering from the University of Cincinnati in 1990, and the Ph.D. in Mechanical Engineering from the University of Notre Dame in 1993.



Dr. Paul S. Schenker is Supervisor, Mechanical and Robotics Technologies Group, Mechanical Systems Engineering and Research Division, Jet Propulsion Laboratory. His current work emphasizes planetary rover development and robotic sampling technologies; he is task manager for NASA/JPL's Sample Return Rover (SRR) and Exploration

Technology Rover Design, Integration, and Field Test R&D efforts ("ET Rover/FIDO" -- a Field Integrated Design & Operations rover prototype supporting the NASA Mars '03-'05 sample return missions, and related terrestrial mission simulations), as well as new NASA tasks on use of cooperating robotic assets/rovers for Mars exploration and future human habitation. Schenker also recently led JPL's Planetary Dexterous Manipulators R&D under NASA funding, work that prototyped a robotic sampling concept that flew on the NASA Mars Polar Lander mission. Schenker's other recent robotics R&D activities include a role as founding co-PI for NASA/MicroDexterity Systems Inc.'s development of a Robot Assisted Microsurgery ("RAMS") high-dexterity tele-operative workstation and a longer standing involvement in various tele-robotic technology and system developments for orbital servicing and autonomous robotic exploration. Schenker is a member of AAAI, IEEE, and SPIE; he is a Fellow and 1999 President of the last. He is widely active in external technical meetings, publications, and university collaborations in the areas of robotics and machine perception, having contributed about 100 archival articles to same. Dr. Schenker received his B.S. in Engineering Physics from Cornell University, and completed his M.S., Ph. D. and postdoctoral studies in Electrical Engineering at Purdue University. Prior to joining JPL/Caltech in 1984, Schenker was with the Electrical Sciences faculty, Brown University, and later the Research Section Chief for Signal & Image Processing, Honeywell Inc.